THE SUN[1]

By FERDINAND ELLERMAN

In choosing the Sun as my subject for discussion in this lecture, I do so for two reasons—first, its preponderating eminence as a celestial object, and second, our utter dependence on it for all forms of life and energy on the Earth, as well as our very existence.

Let us begin by considering the size, distance, mass and other features of the Sun. The distance to the Sun is approximately 93,000,000 miles. Its diameter is 865,000 miles, its volume 1,300,000 times that of the Earth, and its mass 332,000 times that of the Earth. The gravitational force at the visible surface is about 27½ times that on the Earth; a man who weighs 150 pounds would, on the Sun, be attracted with a force of over two tons, and would be crushed by his own weight, were he able to exist under the tremendous heat existing there. The surface temperature of the Sun is about 6,000° C., so that every known substance is in a state of vapor.

Above the brilliant solar surface is a layer of gases called the reversing layer, which is transparent except to the light which it itself emits. If an incandescent gas is produced in an electric spark, arc, or vacuum tube, and is examined with a spectroscope, a series of bright images of the slit appear as bright lines in the spectrum. If, now, strong white light which gives all the colors of the spectrum is made to pass through the gas, and if this light is strong enough to form a continuous spectrum brighter than the bright lines viewed before, they will appear dark on a bright background by their power of absorption; that is, they obstruct the kind and strength of light they themselves emit. In this manner the reversing layer of gases just above the Sun's surface, or photosphere, which by itself would give a spectrum of bright lines, actually produces dark lines in the solar spectrum, because the photosphere below it gives a continuous spectrum. It is by means of these absorption lines, which are compared with the artificial bright lines produced in the laboratory by vaporizing the various substances, that we detect the presence in the Sun of most of the different elements found on the Earth.

[1]A lecture delivered before the Society in Native Sons Hall, San Francisco, on October 14, 1921.

Up to the present time we are certain of the identification of 38 elements, which include the common ones, while gold and the platinum group of metals, except rhodium, palladium and ruthenium, have, so far, evaded detection.

Above the reversing layer is the chromosphere, the atmosphere of lighter gases, such as hydrogen, helium and metals like calcium and magnesium. It is so called from its appearance at the time of a total solar eclipse, when just as the Moon covers the photosphere a pink colored ring is seen for a moment. This color is due mainly to the red line in the spectrum of hydrogen. It is in this layer of gases that the ordinary prominences seem to have their origin.

Let us examine the Sun as a celestial object. Its brilliant disk, a little over half a degree in diameter (the apparent size of a dime held at a distance of 6¼ feet), shining with a brilliance several times that of the core of an electric carbon arc lamp, is too dazzling to look at directly, or through a telescope, without reducing the intensity of the light. This is done by means of smoked glass held before the eyes when looking directly at the Sun, or by means of a polarizing eyepiece attached to the telescope. With such an eyepiece the intensity of the light may be varied to suit the sensitivity of the observer's eye. The Sun may also be examined with telescopes having ordinary eyepieces by projecting its image upon a sheet of white drawing paper. In this manner the chief features of the surface may be well seen. When the Sun is viewed by means of a fairly powerful telescope under good conditions of "seeing" the surface presents a finely divided structure which has been likened to rice grains in appearance.

It will be noticed that the edge of the Sun is not nearly so bright as the center. This is due to the atmosphere of incandescent but absorbing vapors surrounding the Sun, which causes a diminution of the light received from near the edge, since there the light passes through a greater layer of atmosphere. The effect is similar to the decrease in brilliance of the Sun or Moon when observed near the horizon as compared to the view when nearly overhead. Near the east or west edge of the Sun may be seen bright mottled regions, called faculæ. The faculæ are not visible towards the center of the disk as they are very

little, if any, brighter than the surface of the Sun; but being probably at a somewhat higher level they project above at least a portion of the smoky atmosphere which dims the disk near the edge, and thus shine with relatively greater brilliancy.

In the region of the faculæ one finds the sun-spots, which are the visible evidences of regions of disturbance. They range in size from a few hundred miles in diameter to the enormous spots 30,000 to 40,000 miles in diameter, and often appear in groups that extend over 100,000 miles in length and half as much in width. They may appear as single spots, circular in form, changing very little from day to day, and sometimes lasting for several months. In one case a spot was observed to last for 18 months, or about 20 synodic rotations of the Sun upon its axis. The Sun rotates once in 25¼ days, but as the Earth moves along in its orbit in the meantime, it takes about two days longer, making 27¼ days, for the same meridian on the Sun to be at the same place again as seen from the Earth. As the sun-spots are carried across the disk by the Sun's rotation changes in their form from day to day are common. The changes are sometimes very marked, as can be seen by comparing the two photoheliograms in Fig. 1, Plate I, but ordinarily the changes in a day are only small variations in form, the main features remaining recognizable. It is interesting to examine plates taken on successive days and to observe the changes. Plate II shows a series of exposures on ten successive days in which the features just mentioned are well brought out. It will be noticed that spots appear on some days where none was visible the day before and that some spots grow larger, some smaller.

The detail visible in a large spot with a powerful telescope and steady seeing is of extraordinary beauty. The filaments of the inner edge of the penumbra (the semi-dark portion) are plume-like in form. Fine, brilliant tongues stretch into the umbra (the black center) and bridges form across the spots by tongues extending from one side, or by the junction of two tongues coming in from opposite sides of the spot.

The Sun passes through a cycle of sun-spot activity having a duration of 13 or 14 years, with a period of approximately 11 years from one maximum to the next, or from minimum to

minimum. Thus we may and do have spots of both cycles appearing at the same time.

When the spots of a new cycle begin to make their appearance they develop in high latitudes north and south (35° to 40°), and as the cycle progresses the spots appear in lower average latitudes until, when the end is reached, they form very near, and sometimes on, the equator. When at maximum spot activity they form in latitudes about 20° each side of the equator. The last maximum occurred in 1917, about August, and the minimum is expected in the latter part of 1923 or the beginning of 1924.

The cause of the development of a sun-spot is not clearly understood. A number of theories have been proposed, but none is entirely adequate in fitting all forms of spots and their motions. There is, however, very little doubt that sun-spots originate in the interior of the Sun, where temperatures and pressure must be very high as compared to the surface, thus producing strong convection currents, which rise toward the surface and set up whirling vortices similar to terrestrial tornadoes. The cooling of the gases caused by their expansion in the vortex renders them visible as comparatively dark clouds seen against the photosphere.

When the light from a sun-spot is examined with a spectroscope, we find a striking difference between the spectrum of the spot and that of the photosphere. Many lines are strengthened and widened in the spectrum of the spot, and multitudes of fine lines appear in certain regions of the spectrum. For instance, in the green a band of fine lines is due to magnesium hydride, while another series of bands in the deep red is due to titanium oxide. These compounds form at the lower temperatures occurring in the spot, while in the general photosphere the temperature is too high for such compounds to exist, and they are dissociated into their constituent elements.

When a large spot is examined with a powerful spectroscope, certain lines are observed to be double or triple as they cross the spot. The explanation for this is found in the laboratory. When the light of an electric spark is formed between the poles of a powerful magnet, it is found on examination that the magnetic field causes certain lines to be split up into three or more components. By applying an analyzer for polarized light we find

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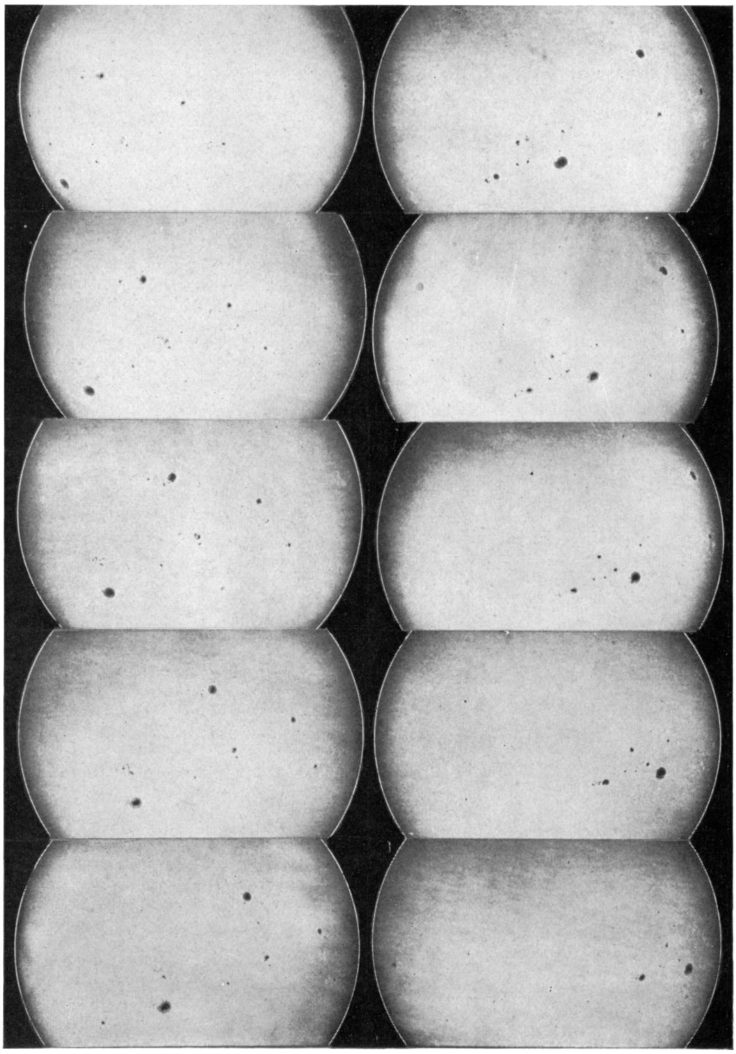

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Portions of the Sun, photographed on ten consecutive days, to illustrate the motion of spots across the Sun's face, due to the solar rotation. The development of spots and changes in form from day to day are also shown.

PLATE II.

the light of the component lines to be polarized, and by applying the same tests to the spot lines we find them to respond in a similar manner to the laboratory lines.

Our inference, then, is that the lines in the spot are affected by a magnetic field, and the sun-spot must, therefore, be a magnet. This can be brought about by the whirl of electrified particles, always present in hot bodies like the Sun, in the vortices or whirlpools which we observe in the vapors above sun-spots. Now, if these electrified particles are traveling in a circular motion, they produce the same effect as an electric current flowing in a coil of wire, which we know is that of a magnet. The spot then creates its own magnetic field by the action of the electric charges which the incandescent atoms carry in their circular motion in the spot.

There are at times violent outbreaks near sun-spots, and if the axis of the spot is directed towards the Earth at the time, it is in the line of fire, so to speak, of the stream of electrified corpuscles or electrons, which are shot out from the regions about the spot in enormous quantities. When these electrons reach the Earth's atmosphere in great numbers they encounter the upper layers of air and give it an electric charge, that is, the air becomes ionized. In the process electric currents are set up, and the induced currents in telegraph lines are sometimes strong enough to interfere seriously with the sending of messages. The aurora is considered to be a manifestation in our upper atmosprhere, caused by the passage of these electrified particles from the Sun. A marked example was the effect produced by the two spots near the center of the Sun on May 13, 1921, when unusually brilliant auroras were observed, and telegraphy seriously hindered.

As previously mentioned, the prominences have their origin in the chromosphere. They are cloud-like masses of gas floating in the upper atmosphere of the Sun, sometimes for days, and reaching to great heights at times. Ordinarily they rise to 40,000, 50,000 or 60,000 miles in height, but occasionally they reach 300,000 miles, and two cases have come to my knowledge where the upper part of a prominence rose more than 400,000 miles above the photosphere. There are several types of prominences. One consists of quiescent clouds, changing slowly and

then slowly fading away. Another type resembles that just mentioned, but for some unknown cause begins to rise and then suddenly seems to blow up, as if impelled by a terrific repulsive force from the Sun, and reaches the enormous heights already mentioned. A third type consists of jet-like curved forms that begin and end at the Sun's limb. These are found in the vicinity of active sun-spots, and are doubtless connected with eruptions. Then there are the eruptive prominences which rise from the surface with high velocities and reach great heights, and fade away rapidly.

It was my good fortune to make the first photograph of a large eruptive prominence on March 25, 1893, when a prominence excited my attention by rising from about 60,000 miles in height to 100,000 miles in the few minutes elapsing while the rest of the Sun's edge was being examined. Three exposures with the spectroheliograph showed the prominence to have a height of 120,000, 160,000, and 280,000 miles, with time intervals of 6 and 8 minutes, ascending 160,000 miles in 24 minutes, or at an average rate of about 110 miles per second! In examining the brilliant base of the prominence with the spectroscope, I found the red line of hydrogen in the prominence to consist of two lines, one displaced towards the red, the other toward the violet of its normal position. By measuring this displacement and computing the velocity with which the particles must have been moving to cause such displacements, I found a velocity of nearly 120 miles per second towards us and from us. Here seemed to be a distinct case of an explosive eruption carrying a mass of gas high into the upper atmosphere, which after reaching a certain height rapidly disintegrated and vanished, for when I again looked for the prominence after the last exposure it was no longer there, but had faded into invisibility.

When the prominences are observed at the edge of the Sun, they can be seen by means of a spectroscope attached to the telescope. This is because the bright lines of hydrogen, especially the red line, are so much brighter than the continuous spectrum of the sky just beyond the Sun's edge that the slit can be widened enough to include a considerable portion of the prominence at a time. By moving the telescope so as to move the image over the slit, all of the prominence can be thus viewed.

When prominences are projected against the disk of the Sun, it is generally not feasible to observe them visually, and photography must be brought into play. This is done in the following manner: A dark line in the solar spectrum, due to some known light element such as hydrogen, is selected. A spectroscope is so adapted that a second slit can be used to replace the eyepiece (in which case it is called a spectroheliograph); the second slit is set so that the hydrogen line is transmitted, while all other light is cut off by the slit jaws. By moving the spectroheliograph so that the first slit passes across the Sun's image, and the second slit passes in front of a stationary photographic plate, a picture of the Sun as seen in hydrogen light will be built up by the varying intensity of the line caused by the varying thickness of the hydrogen clouds scattered over the Sun; and if a prominence is projected on the disk it will reveal itself by the strong absorption of its great mass of vapor. (See these Publications, Feb., 1918.) By means of the spectroheliograph the Sun's surface can be photographed to show the clouds of hydrogen, calcium, iron, sodium, and magnesium. The last two, though bright, are not conspicuous. Iron shows fairly strong clouds, resembling the low level calcium structure. Calcium shows strong brilliant clouds scattered over the Sun's disk, and especially in the region of sun-spots. These calcium clouds, or flocculi, as we call them, are always associated with regions of sun-spots and faculæ. By their relative brightness one has some clue as to the intensity of the disturbance lying beneath them. They are the first evidence we have of the formation of a spot or group of spots. Whenever a region on the Sun's surface shows strong calcium flocculi, even though nothing is visible on the direct image of the Sun, it is very likely that a spot will develop in this region. Hydrogen is intimately associated with calcium, but its vapors in general show as absorption phenomena and appear as dark clouds. In the vicinity of sun-spots, however, it often happens that very brilliant hydrogen clouds are photographed, and in many cases the underlying spots are covered over by the calcium or hydrogen clouds, and are not visible on the spectroheliograms.

The lines in the solar spectrum are not all produced at the same level. Some have their origin high in the Sun's atmos-

phere, others low, while the majority are produced at intermediate levels. Hydrogen, the lightest element, has five lines in the visible spectrum. The red line ($H\alpha$) represents the highest level. The blue-green ($H\beta$) is somewhat lower, the other lines following at still lower levels. By selecting the different lines of hydrogen in using the spectroheliograph and making several exposures in quick succession, one can photograph a number of cross-sections of a prominence on the disk, similar to the horizontal cross-sections of a tree, and in this way obtain a very comprehensive view of the prominence. In like manner one can secure cross-sections of the calcium clouds by employing the broad H or K line, where the center of the line represents the highest level, while the wings represent lower and lower levels, as one selects portions of the band farther and farther from the center. The lowest level calcium vapor seems to have the same form and appearance as the iron vapors photographed through the iron line at wave length 4046A.

Let us now discuss the Sun from the viewpoint of its influence upon the Earth.

Having a mass equal to 332,000 earths, its force of attraction is sufficient at the distance of 93,000,000 miles to hold the Earth captive in its orbit. Now, the mass of the Earth is approximately 6.6×10^{19} tons, and as it is traveling in its orbit at a rate of about 19 miles per second, the attractive force of the Sun and Earth combined is such that to replace it, would require about nine No. 4 telegraph wires per square inch of the projected hemisphere facing the Sun. Or, stating it in a different way, the attraction of the Sun and Earth is about equal to the breaking strain of a steel rod 3,000 miles in diameter!

Thus the Sun holds the planets in their orbits and supplies them with energy, mainly in the form of light and heat.

The temperature of the solar surface, as already mentioned, is about 6,000° C. What the interior temperatures may be can be determined only by calculation. It has been computed by competent authority that the temperature at the center of the Sun is probably millions of degrees. At such high temperatures, liquefaction is impossible even at the enormous pressure which must exist there.

With such enormous temperature and pressure at the center,

and the cooling effect at the surface due to loss of heat by radiation, strong convection currents must exist below the photosphere, bringing fresh supplies of energy to replace the loss.

The amount of heat that the Earth receives from the Sun is approximately two calories (1.95) per square centimeter per minute. The calorie is the heat unit of measurement, and represents the amount of heat required to raise 1 gram of water 1° centigrade at a temperature of 15° C.

This energy converted into its mechanical equivalent represents 1.4 kilowatts per square meter, or 1.6 horsepower per square yard per minute. This is the amount of energy received at the outer edge of our atmosphere, but in passing through the atmosphere a considerable portion is absorbed. Although the sky seems transparent to the eye, nevertheless it may contain a considerable amount of invisible water vapor, which acts as an absorbing screen. Abbot finds that at Washington, D. C., on a clear day, with the Sun within 45° of the zenith, from 1.15 to 1.45 calories per square centimeter per minute are received. On Mount Wilson, over one mile elevation, the observed values range from 1.45 to 1.62 calories, and on Mount Whitney, nearly three miles elevation, they reach 1.75 calories.

The amount of energy received at the distance of the Earth is sufficient to melt each year a shell of ice having a diameter of 186,000,000 miles and a thickness of 425 feet. Or, putting it differently, let us suppose that the Sun were surrounded by a layer of ice about 40 feet thick. If all the heat were utilized, the ice would be melted in one minute of time. Or, if a column of ice 45 miles in diameter were formed and darted at the Sun with the velocity of light (186,000 miles per second), and if by any means all the energy of the Sun could be concentrated upon it, the point of it would be melted as fast as it approached; or, again, if there were a rod of ice a little more than two miles in diameter reaching from the Earth to the Sun, and if as before all the Sun's energy were concentrated upon it, the rod of ice would be melted in, not one minute, but *one second,* of time, and be vaporized in seven seconds more! This amount of energy is too vast for the human mind to grasp thoroughly. Think of a quantity of heat being radiated into space sufficient to melt 300,000,000 (three hundred million) cubic miles of ice per sec-

ond of time! All this energy is radiated into space continuously, and represents the amount of heat produced by combustion of a layer of anthracite coal 3.8 inches thick every minute, and is equivalent to a continuous production of twelve thousand horse-power per square foot of the Sun's whole surface. Of this amount the Earth intercepts a most insignificant fraction, namely, the 1/2,200,000,000 part.

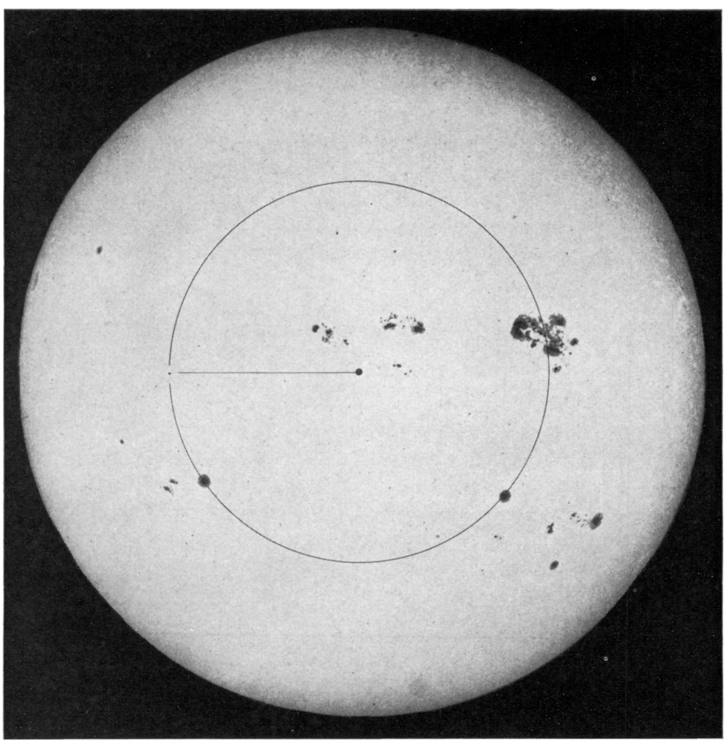
What keeps up the Sun's temperature, or what supplies the energy which is lost by radiation? That the Sun has been radiating at approximately its present rate for millions of years is a fact, and geologists show that the Earth has changed but little in temperature for probably 50,000,000 years. Combustion is out of the question, for if the Sun were composed of solid coal and produced its heat by burning, it would not last five thousand years.

Lord Kelvin calculated the amount of heat which would be produced by each of the planets falling into the Sun from its present orbit. The results are as follows, the heat being expressed in years and days during which it would maintain the Sun's present rate of radiation:

Mercury	6 years	219 days
Venus	83 "	326 "
Earth	95 "	19 "
Mars	12 "	259 "
Jupiter	32,254 "	
Saturn	9,652 "	
Uranus	1,610 "	
Neptune	1,890 "	
	45,604 years	

That is, a mass equal to less than one-hundredth part of the Earth's mass, falling annually upon the Sun, would maintain its rate of radiation. But such an increase of matter in the mass of the Sun would be made evident by the acceleration of the motion of the planets in their orbits.

Of the theories advanced to explain the maintenance of heat, that proposed by Helmholtz in 1853 was long generally accepted, but now seems inadequate. This theory states that the Sun's radiation is maintained by the falling of the particles composing



The Sun, photographed on August 12, 1917. The circle represents the size of the Moon's orbit, the dot representing the size of the Moon, while the dot in the center represents the size of the Earth.

PLATE III.

the Sun itself. Thus a shrinking of the Sun's diameter of 270 feet per year would suffice to keep up the supply of energy. At this rate the Sun would have shrunk to about half its size in 7,000,000 years, if radiating an amount of energy equal to its present rate. This is wholly incompatible with the results of recent research and other sources of energy must be sought.

The energy of the Sun is transmitted through space and reaches the Earth in the form of waves—light and heat. Traveling at the rate of 186,000 miles per second and having a wave-length for the visible rays of from 0.0004 mm. to 0.00075 mm., the vibrations have frequencies averaging 550,000,000,000,000 per second.

It is upon these apparently insignificant waves that all light, heat, power, and the growth of all living things depend. Suppose, if you will, that the Sun were to be instantly removed, and that all its forces ceased to act on the solar system. The Earth and the other planets, no longer held in their orbits by the Sun's attraction, would go off at a tangent and become lone wanderers in space. The Earth would be plunged into utter darkness, save for the light of the stars. The Moon and planets would no longer shine by reflected sun light. No heat would be received, but, on the contrary, the Earth would rapidly lose its heat by radiation, the moisture in its atmosphere would be precipitated in the form of snow, covering the higher regions first, then lower down, and finally the oceans would give their latent heat and become sheets of ice. Plant life would cease in a short time—a few days; animals would succumb next, and man, by having stored food and making use of artificial heat, would be able to exist a short time after all other forms of life had vanished. The Earth would become a dead world, encrusted with ice and snow. One authority states that inside of one month all life on the Earth would cease.

How is this radiant energy utilized? It is stored by animals and plants as potential energy. The plants need the action of the sun light on chlorophyl to prepare the plant foods which the roots bring up out of the ground in the form of mineral salts. The action of the plants is accelerated by the Sun's rays. The vegetable foods are simply solar energy stored up in a form

assimilable by animals. Animals are another form of converted energy, in a form suitable for food for man.

In ages past the Sun's energy was stored up in the luxuriant growth of the carboniferous period. Today we make use of this energy in the various forms of coal. The same may be said regarding asphaltum, mineral oils, and natural gas, which are obtained from below the Earth's surface. These are the main sources of stored-up energy which man makes use of for his comfort and to carry on his commerce.

There is another form of energy which is being more and more brought into usefulness. The heat of the Sun's rays causes convection currents in the Earth's atmosphere, and as the air passes over the ocean, evaporation of the water takes place. The tiny particles are carried by the wind until, being cooled in rising to higher elevations, they are precipitated in the form of rain and snow. Thus the Sun lifts the water out of the ocean and deposits it in high places in the mountains, giving us enormous sources of power for the production of light and heat and electrical energy.

Before the advent of the steam engine, all commerce on the seas was carried on by the energy imparted by the winds. Today wind power is still used to a great extent in operating windmills of various types. The erosion of our mountains, the formation of the giant chasms like the Grand Canyon of the Colorado, Yellowstone, Royal Gorge, the Garden of the Gods, and all similar phenomena produced by wind and water have been made possible by the conversion into other forms of energy of the little light waves from the Sun.

Most of these light waves pass through glass very readily, but when they strike an absorbing medium they are converted into heat. Now, heat waves are very long compared with light, and they do not readily pass through glass. This principle is used in green houses. The clouds and even invisible water vapor are great absorbers of heat rays.

Today, as in times past, the storing of the Sun's energy is going on, for the use of future generations. We need only to look at our forests. Here we have evidence of a storage of energy which has gone on for a period of 4,000 years, and is still continuing. If a thousandth part of the energy which the

Earth receives is converted into stored energy, it will be sufficient to meet the future demands.

Thus, no matter what we see or do, we are continually making use of solar energy in some form or other.

There is one solar phenomenon which I have left for my conclusion, as it is the most beautiful and inspiring object which the heavens present, namely, the solar corona at the time of an eclipse of the Sun. This halo extends irregularly around the Sun to a distance of about 2,000,000 miles in the coronal streamers. At the instant the moon covers the Sun's disk, the beautiful pinkish pearly light of the corona surrounding the Sun becomes visible. At the Sun's edge are the crimson-colored prominences, far surpassing in brilliancy the brighter parts of the corona. It is the wonderfully delicate and intricate detail of the coronal structure that holds one's attention when viewing it through a telescope of moderate power. The form of the corona changes from one eclipse to another, but there seems to be a definite type of structure which presents itself at the time of maximum sun-spot activity. Similarly, another type is seen at the time of sun-spot minimum.

The light of the corona is principally sun light reflected from the minute particles of which it is composed, but a portion of it comes from the unknown element or substance which has been given the name of coronium, which gives rise to a strong line in the green part of the spectrum. This element does not seem to be present in the lower solar atmosphere, at least no line corresponding to the coronal line is visible in the solar spectrum.

On September 10, 1923, at about one o'clock in the afternoon, a total eclipse of the Sun will occur, visible at a few places in southern California, and through Mexico. The northern limit of totality just about touches Lompoc, just misses Santa Barbara, and reaches the mainland again near Miramar. San Nicholas and San Clemente Islands are on, or very near, the central line of totality. The duration of totality will be about three and one-half minutes. Conditions should be very favorable for clear skies on the line of the eclipse, as fogs and clouds are not likely to interfere at that time of the year.

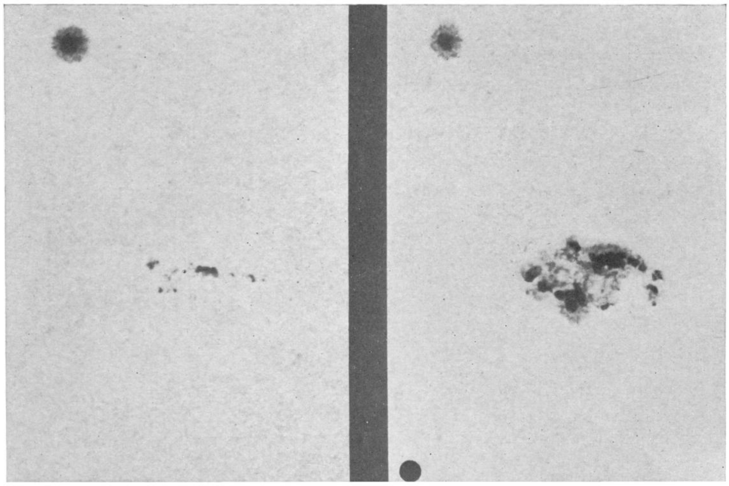


FIG. 1. Rapid development of a sun-spot group. The time interval between exposures is $24^h 5^m$. The black disk at lower edge represents the size of the Earth.

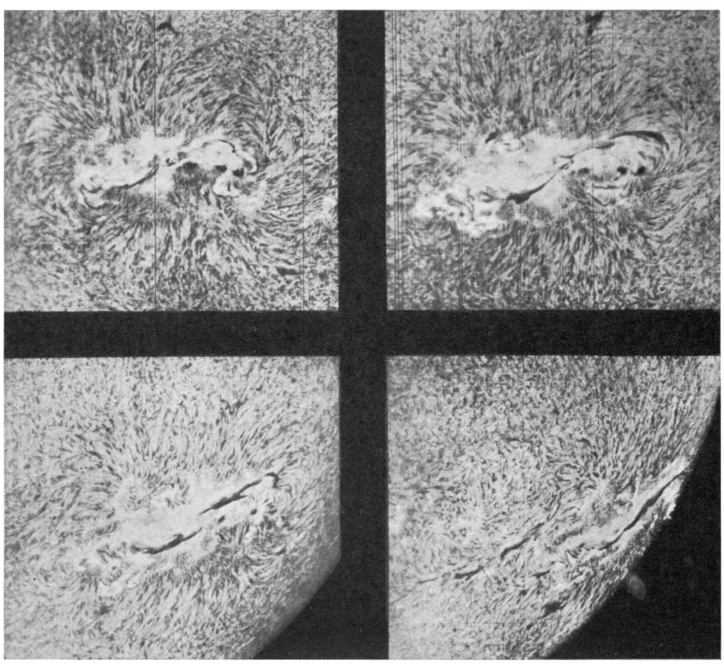


FIG. 2. Southwestern portion of the Sun photographed on August 3, 5, 7 and 9, 1915, with the 13-foot spectroheliograph, employing the red line of hydrogen (Hα) to show the hydrogen clouds around and over an extensive sun-spot group.

PLATE I.